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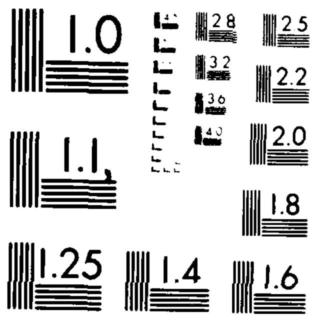

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Report SAM-TR-82-47

DECOMPRESSION PROCEDURES FOR FLYING AFTER DIVING, AND DIVING AT ALTITUDES ABOVE SEA LEVEL

Validation Tests

Bruce E. Bassett, Lieutenant Colonel, USAF, BSC

December 1982

Final Report for Period May 1979 – June 1982

USAF SCHOOL OF AEROSPACE MEDICINE
Aerospace Medical Division (AFSC)
Brooks Air Force Base, Texas 78235

NOTICES

This final report was submitted by personnel of the Crew Protection Branch, Crew Technology Division, USAF School of Aerospace Medicine, Aerospace Medical Division, AFSC, Brooks Air Force Base, Texas, under job order 7930-14-20.

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The voluntary informed consent of the subjects used in this research was obtained in accordance with AFR 169-3.

The Office of Public Affairs has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

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UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: SAM-TR-82-47	2. GOVT ACCESSION NO.: AD-A125 C39
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): DECOMPRESSION PROCEDURES FOR FLYING AFTER DIVING AND DIVING AT ALTITUDES ABOVE SEA LEVEL Validation Tests	5. TYPE OF REPORT & PERIOD COVERED: Final Report May 1979 - June 1982
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Bruce E. Bassett, Lieutenant Colonel, USAF, BSC	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: USAF School of Aerospace Medicine (VNB) Aerospace Medical Division (AFSC) Brooks Air Force Base, Texas 78235	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 62202F 7930-14-20
11. CONTROLLING OFFICE NAME AND ADDRESS: USAF School of Aerospace Medicine (VNB) Aerospace Medical Division (AFSC) Brooks Air Force Base, Texas 78235	12. REPORT DATE: December 1982
	13. NUMBER OF PAGES: 41
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Bends	Flying and diving
Decompression sickness	Hyperbaric and altitude chambers
Diving	Tolerances
Diving and flying	Venous gas embolisms at altitudes

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Decompression procedures were developed for divers exposed to reduced atmospheric pressures shortly after diving. These procedures involved human subjects and multiple diving exposures in laboratory hyperbaric and altitude chambers. The studies were conducted in two phases. In Phase I, six exposure schedules were tested using 16 - 20 subjects per exposure. The six exposures tested--dive depth in feet sea water/no-decompression limit (minutes) for direct ascent to 10,000 ft--were: 130/7; 100/10; 80/14; 60/20; 40/34; and

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued)

10.75/1440. Exercise was performed at depth. Subjects remained at 10,000 ft for 4 hr, during which they exercised and breathed ambient chamber air. Then the subjects went to 16,000 ft for 1 hr, and used a diluter-demand oxygen system. Subjects were monitored for venous gas emboli (vge) by means of a precordial Doppler ultrasonic bubble detector. At 10,000 ft: 11.8% of the exposures produced vge, and 6.4% of exposures were terminated because of bends or high vge scores. At 16,000 ft: 4.9% of the 103 exposures ended with bends or vge. Phase II used three exposures--100/10, 80/14, and 60/20 schedules--and altitude exposures were changed from 10,000 to 8,500 ft, and from 16,000 to 14,250 ft. Of the 57 subject exposures in Phase II, none developed bends or high vge scores at 8,500 ft. At 14,250 ft, 5.3% developed bends or high vge scores. Because of these results, the surfacing ratio limits of the U.S. Navy Standard Air Decompression Tables were revised. The revised ratios were shown to allow for calculation of safer flying-after-diving schedules. Appendix A of this Report contains the no-decompression limits for: dives conducted at sea level, followed by immediate ascent to altitudes up to 10,000 ft; and dives made within 12 hr of arrival at altitudes up to 10,000 ft. Appendix A also contains no-decompression limits for dives made 12 hr after arrival at altitudes up to 10,000 ft. Recommendation is made for the adoption of these schedules (Appendix A) for military use.

PREFACE

The USAF Aerospace Rescue and Recovery Service, Military Airlift Command, requested that the Aerospace Medical Division, USAF School of Aerospace Medicine (USAFSAM), verify and validate decompression schedules and procedures for flying after diving and diving at altitude. Because the U.S. Navy, under Tri-Service agreements, is the office of primary responsibility for military diving problems, a suggested validation program was forwarded to the Bureau of Medicine, U.S. Navy. The U.S. Navy and the Naval Medical Research and Development Command (NMRDC), because of potential U.S. Navy and U.S. Army interest in the problem area, suggested that a Tri-Service meeting be convened to review the suggested validation program.

The USAF Surgeon General requested that the Tri-Service Aeromedical Research Panel (TARP) discuss the topic at their meeting, 1-3 December 1976. The TARP recommended that a separate meeting be held on the subject. This meeting was conducted at the USAFSAM, 15 December 1976; and the results were forwarded to the TARP chairman for discussion as an action item at the March 1977 TARP meeting. The TARP meeting approved the recommendations, for the validation program (the subject of this report), made as a result of the special Tri-Service meeting of 15 December 1976.

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DECOMPRESSION PROCEDURES FOR FLYING AFTER DIVING
AND DIVING AT ALTITUDES ABOVE SEA LEVEL

Validation Tests

I. PURPOSE AND OBJECTIVES

These tests were necessary to validate decompression procedures for military divers required to fly in aircraft after diving exposures, or to dive at altitudes above sea level.

II. BACKGROUND

Calculation and validation tests of decompression procedures for flying after diving, within a limited range of exposures, were conducted under a NASA contract by Edel et al. (1), and by Edel (2, 3, 4). The present standard for validation testing is based on operational requirements which are beyond the range of procedures validated in these NASA tests. Specifically, requirements exist for safe exposure times which allow direct ascent to altitude after dives to various depths.

Other procedures for flying after diving have been published by Stubbs et al. (5), Cross (6), and Smith (7), and in the National Oceanic and Atmospheric Administration (NOAA) Diving Manual (8). As far as can be determined, however, none of these procedures have been validated by manned testing.

Decompression tables and procedures have also been recommended, for diving at elevations above sea level, by Cross (6), Smith (7), Bell (9), Bell and Borgwardt (10), and Boni et al. (11). With the exception of the last reference, none of these recommendations or tables have been validated by manned testing.

On the basis of present and future operational requirements for military divers of the U.S. Air Force, U.S. Navy, and U.S. Army, a need exists: to evaluate decompression models, procedures, and recommendations for flying after diving and for diving at altitudes above sea level; to establish an acceptable model, and calculate decompression tables and exposure profiles from this model; and to perform manned validation testing of the chosen decompression model and exposure profiles. The goals of this program are to provide safe and acceptable decompression procedures both for flying after diving and for diving at altitudes to meet the operational requirements, scheduling commitments, and training objectives of military divers of all three of the armed services.

III. EXPERIMENTAL METHODS

A. Derivation of limiting tissue tensions (M_D values) for: hyperbaric exposures followed by immediate ascent to altitude; or, for hyperbaric exposures conducted at elevations above sea level

1. The M_D Values and Ratios

The starting point for deriving limiting tissue tensions in this study was the U.S. Navy Standard Air Decompression Tables (12), because all divers in the armed services use these Tables in their military diving.

The single determining parameter in calculating decompression tables is the M_D value. The M_D value is the maximum allowable tissue nitrogen pressure that can be tolerated by a given tissue compartment (half-time tissue) during pressure reduction. When the maximum allowable tissue tension at a given depth, D, is related to the total hydrostatic pressure at that depth, a ratio is obtained:

$$R_D = M_D/A,$$

in which

R_D = maximum allowable supersaturation ratio at depth D

M_D = maximum allowable tissue nitrogen tension, given for depth D (usually for 10-ft increments); referred to as M_D value. Normally expressed in: feet of sea water absolute, fswa

A = absolute pressure at the depth where the M_D value is applied, expressed in fswa. A = D + 33 for sea-level conditions where D = gage depth in fsw.

2. The M_D values from the U.S. Navy Standard Air Decompression Tables (12)

Two sets of M_D values are available for calculating air decompression tables for sea-level dives. One (Table 1) is the set of M_D values used in the U.S. Navy Standard Air Decompression Tables. Examination of Table 1 reveals the following:

The slowest tissue considered has a half-time of 120 min.

While the change in maximum allowable nitrogen tension with 10 fsw depth varies, the $\Delta M_D/\Delta 10$ fsw is reasonably constant for each half-time; the maximum allowable ratios increase as depth decreases.

Since the $\Delta M_D/\Delta 10$ fsw values are essentially constant, the M_D values vs. depth will graphically plot a straight line

TABLE 1. U.S. NAVY STANDARD AIR DECOMPRESSION TABLES M_D VALUES AND RATIOS

A. The M_D Values (fswa)

Tissue half-times		5	10	20	40	80	120
M_0	leave 10 fsw reach surface	104	88	72	58	52	51
M_{10}	leave 20 fsw reach 10 fsw	126	107	90	72	65	64
M_{20}	leave 30 fsw reach 20 fsw	150	128	106	87	78	76
M_{30}	leave 40 fsw reach 30 fsw	174	148	124	99	90	88
M_{40}	leave 50 fsw reach 40 fsw	195	167	141	113	103	101
M_{50}	leave 60 fsw reach 50 fsw	220	189	158	128	115	114
M_{60}	leave 70 fsw reach 60 fsw	242	208	174	141	128	126
M_{70}	leave 80 fsw reach 70 fsw	263	228	192	156	142	140
	Average $\Delta M/\Delta 10$ fsw:	22.7	20.0	17.1	14.0	12.9	12.7

B. The Ratios (R_D Values)

Tissue half-times		5	10	20	40	80	120
R_0	reach surface	3.15	2.67	2.18	1.76	1.58	1.55
R_{10}	reach 10 fsw	2.93	2.49	2.09	1.67	1.52	1.49
R_{20}	reach 20 fsw	2.83	2.42	2.00	1.64	1.47	1.43
R_{30}	reach 30 fsw	2.76	2.35	1.97	1.57	1.43	1.40
R_{40}	reach 40 fsw	2.67	2.29	1.93	1.55	1.41	1.38
R_{50}	reach 50 fsw	2.65	2.28	1.90	1.54	1.39	1.37
R_{60}	reach 60 fsw	2.60	2.24	1.87	1.52	1.38	1.35
R_{70}	reach 70 fsw	2.55	2.21	1.86	1.51	1.38	1.36

which can be extrapolated to altitudes above sea level. (These extrapolations are discussed later in the text.)

3. Workman M_0 Values

The other set of M_0 values (Table 2) were developed by Dr. Robert Workman, Captain, USN, MC (13). These M_0 values reveal the following:

The slowest tissue considered has a half-time of 240 min.

The $\Delta M_0/\Delta 10$ fsw value is constant for each half-time, and the maximum allowable ratios increase as depth decreases. The M_0 values vs. depth also plot a straight line.

4. Comparison of M_0 Values

Comparisons of Tables 1 and 2 have revealed numerous differences. The M_0 and R_0 values are the same, in both sets, for the 5-, 10-, and 20-min half-time tissues. The Workman M_0 and R_0 values for the 40-min tissue are less than the U.S.N. M_0 and R_0 values, while the Workman M_0 and R_0 values for the 80- and 120-min half-time tissues are greater than the respective U.S.N. values. The Workman $\Delta M_0/\Delta 10$ fsw values are smaller than the U.S.N. values for the 5-, 10-, 20-, and 120-min half-time tissues, and are essentially the same for the 40- and 80-min half-time tissues in the two sets. The M_{10} through M_{30} and R_{10} through R_{30} values are equal in the two sets for the 120-min half-time tissue, but become smaller in the Workman set at M_{40} and R_{40} through M_{70} and R_{70}. With the exception of the 80-min half-time tissue and, in part, the 120-min half-time tissue, the Workman set of values is more conservative than that used in constructing the U.S.N. Standard Air Tables.

5. Linear Extrapolations of M-Values for Altitude Exposures

As previously discussed, since the $\Delta M_0/\Delta 10$ fsw values are reasonably constant in both sets of values, the M_0 vs. depth relationship plots as a straight line when presented graphically. Extension of these lines to elevations above sea level would then, presumably, permit maximum allowable tissue tensions to be determined for hyperbaric exposures at any given altitude. Listed in Tables 3 and 4 are the M_0 values obtained in this manner for altitudes of 4,500, 7,000, and 9,500 ft above sea level. Also presented are the ratios calculated for these values. Only the M_0 and R_0 (i.e., surfacing) values are presented in these two tables.

Examination of Tables 3 and 4 reveals the following information: While the Workman values are generally more conservative than the U.S.N. Standard Air Decompression Table values when compared at depths <u>below</u> sea level, the reverse becomes true when these two sets of values are <u>linearly</u> extrapolated to altitudes <u>above</u> sea level. Thus, except for the 40-min tissue, the Workman values <u>allow</u> generally greater tissue tensions and larger ratios than the U.S.N. Standard Air Decompression Table values when extrapolated to altitudes above sea level.

TABLE 2. WORKMAN'S M_D VALUES AND RATIOS

A. The M_D Values (fswa)

Tissue half-times		5	10	20	40	80	120	160	200	240
M_0	leave 10 fsw reach surface	104	88	72	56	54	52	51	51	50
M_{10}	leave 20 fsw reach 10 fsw	122	104	87	70	67	64	63	62	61
M_{20}	leave 30 fsw reach 20 fsw	140	120	102	84	80	76	74	73	72
M_{30}	leave 40 fsw reach 30 fsw	158	136	117	98	93	88	86	84	83
M_{40}	leave 50 fsw reach 40 fsw	176	152	132	112	106	100	97	95	94
M_{50}	leave 60 fsw reach 50 fsw	194	168	147	126	119	112	109	106	105
M_{60}	leave 70 fsw reach 60 fsw	212	184	162	140	132	124	120	117	116
M_{70}	leave 80 fsw reach 70 fsw	230	200	177	154	145	136	132	128	127
Average $\Delta M/\Delta 10$ fsw:		18	16	15	14	13	12	11.5[a]	11	11

B. The Ratios (R_D Values)

Tissue half-times		5	10	20	40	80	120	160	200	240
R_0	reach surface	3.15	2.67	2.18	1.70	1.64	1.58	1.55	1.55	1.52
R_{10}	reach 10 fsw	2.84	2.42	2.02	1.63	1.56	1.49	1.47	1.44	1.42
R_{20}	reach 20 fsw	2.64	2.26	1.92	1.58	1.51	1.43	1.40	1.38	1.36
R_{30}	reach 30 fsw	2.51	2.16	1.86	1.56	1.48	1.40	1.37	1.33	1.32
R_{40}	reach 40 fsw	2.41	2.08	1.81	1.53	1.45	1.37	1.33	1.30	1.29
R_{50}	reach 50 fsw	2.34	2.02	1.77	1.52	1.43	1.35	1.31	1.28	1.27
R_{60}	reach 60 fsw	2.28	1.98	1.74	1.51	1.42	1.33	1.29	1.26	1.25
R_{70}	reach 70 fsw	2.23	1.94	1.72	1.50	1.41	1.32	1.28	1.24	1.23

[a] The M_D values are calculated using the $\Delta M/\Delta 10$ fsw of 11.5, but the values are rounded off to the next greater whole number.

TABLE 3. LINEAR EXTRAPOLATIONS OF U.S.N. STANDARD AIR DECOMPRESSION TABLE M_0 VALUES AND RESULTING RATIOS (R_0 VALUES)

Altitude	Absolute pressure (fswa)		Tissue half-times 5	10	20	40	80	120
Sea level	33	M_0	104	88	72	58	52	51
		R_0	3.15	2.67	2.18	1.76	1.58	1.55
4,500 ft	28	M_0	92.7	78.0	63.5	51.0	45.6	44.7
		R_0	3.31	2.75	2.27	1.82	1.63	1.59
7,000 ft	25.5	M_0	87.0	73.0	59.2	47.5	42.3	41.5
		R_0	3.41	2.86	2.32	1.86	1.66	1.63
9,500 ft	23	M_0	81.3	68.0	54.9	44.0	39.1	38.3
		R_0	3.53	2.96	2.39	1.91	1.70	1.67
Average $\Delta M/\Delta 10$ fsw:			22.7	20.0	17.1	14.0	12.9	12.7

TABLE 4. LINEAR EXTRAPOLATIONS OF WORKMAN'S M_0 VALUES AND RESULTING RATIOS (R_0 VALUES)

Altitude	Absolute pressure (fswa)		Tissue half-times 5	10	20	40	80	120	160	200	240
Sea level	33	M_0	104	88	72	56	54	52	51	51	50
		R_0	3.15	2.67	2.18	1.70	1.64	1.58	1.55	1.55	1.52
4,500 ft	28	M_0	95	80	64.5	49	47.5	46	45.3	45.5	44.5
		R_0	3.39	2.86	2.30	1.75	1.70	1.62	1.62	1.63	1.59
7,000 ft	25.5	M_0	90.5	5.76	60.8	45.5	44.3	43	42.4	42.8	41.8
		R_0	3.55	2.98	2.38	1.78	1.75	1.69	1.66	1.68	1.64
9,500 ft	23	M_0	86	72	57	42	41	40	39.5	40	39
		R_0	3.75	3.13	2.48	1.83	1.78	1.74	1.72	1.74	1.70
$\Delta M/\Delta 10$ fsw:			18	16	15	14	13	12	11.5	11	11

Another anomaly is found in comparing the M_D and R_D values within the Workman set of values. At sea level, the M_D and R_D values decrease with increasing length of half-times, except for the 160- and 200-min compartments which have the same values. At depths from 10 to 70 ft, the relationship of decreasing M_D and R_D values with increasing half-time holds (refer to Table 2). When extrapolated to altitude, however, the 200-min half-time M_D and R_D values are greater in all cases than the 160-min half-time values.

A final set of conditions was examined in order to further elucidate the apparent shortcomings of the linear extrapolation of M_D values and thus to provide for hyberbaric exposures at altitudes above sea level. Since 26.1 fswa represents the tissue nitrogen tension in the body of man who is equilibrated at sea level (i.e., 0.791 X 33 fswa), we calculated the altitudes at which the linear M_D values attained this value for nitrogen tension. Shown in Table 5 is this information for only the longer half-times (i.e., 120 - 240 min).

TABLE 5. ALTITUDES AT WHICH M_D = 26 FSWA FOR THE 120-, 160-, 200-, AND 240-MIN HALF-TIME TISSUES OBTAINED USING LINEAR EXTRAPOLATED M_0 VALUES

Tissue half-time	120 min	160 min	200 min	240 min
U.S.N. values	23,000 ft	N/A	N/A	N/A
Workman's values	26,500 ft	27,000 ft	29,000 ft	27,000 ft

If the linear extrapolations are valid, then the altitudes presented in Table 5 should represent the threshold altitudes for decompression sickness in an individual equilibrated at sea level. Obviously these altitudes cannot be safely attained; and the conclusion is that the linear extrapolations of M values, either the U.S. Navy or the Workman values, allow supersaturation ratios which would be unsafe for calculation of altitude diving tables.

6. Extrapolation of M-Values for Altitude Exposures Using Constant Critical Ratios

In the theoretical basis for decompression, the driving force for phase separation of a gas in a liquid is reflected in the amount of overpressure of gas which is present when compared to the overall force tending to keep gases in solution, i.e., the total barometric or hydrostatic pressure. Thus, the concept of critical supersaturation ratios has evolved since the studies of Haldane in 1906 (14). "Supersaturation" is defined as the state when the inert gas tension exceeds the total barometric or hydrostatic pressure on the

body; and the "Critical Supersaturation Ratio" is the value of PN_2/P_B which, if exceeded, causes symptoms of decompression sickness in some proportion of the population exposed. In the years devoted to the development of the U.S. Navy Standard Air Decompression Tables, a set of critical supersaturation ratios for six theoretical tissue compartments have been empirically derived. Workman further refined these values and extended them to include three additional slower tissue compartments.

How valid are these critical ratios? The U.S. Navy Standard Air Decompression Tables, as used by U.S. Navy divers, have a reasonable safety record--with an incidence of decompression sickness ranging from 0.03% to 0.41%. As modified for use in USAF hyperbaric chambers, the incidence is even lower. The incidence for tables using the generally more conservative Workman's values is not known, because such tables are not in general use. Consequently, for determining maximum allowable tissue nitrogen tensions (M_D values) for hyperbaric exposures at altitudes above sea level, the most logical method would seem to be to use the critical ratios employed in the sea-level tables to generate such M_D values. Such M_D values could then be used to generate new tables for diving at altitudes above sea level and for flying after diving at sea level. We anticipated that the use of M_D values derived on the basis of the same ratios used for sea-level diving would generate decompression profiles with the same degree of safety.

In Tables 6 and 7 are presented the M_0 values obtained by keeping the R_0 constant for altitudes of 4,500, 7,000, and 9,500 ft above sea level for the U.S.N. and Workman sets of values. Again, only the M_0 values (surfacing values) are presented in these two Tables.

Examination of Tables 6 and 7, in comparison with Tables 3 and 4, reveals the following:

> Extrapolation of M_0 values, using a constant R_0 results in values which are less than those obtained using the linear extrapolation (i.e., constant $\Delta M_D/\Delta 10$ ft in both sets of values).

Based on absolute values for M_0 and R_0, the most conservative set of values would be obtained by using Workman's values for the 40-, 160-, 200-, and 240-min half-time tissues, and the U.S.N. Standard values for the 80- and 120-min half-time tissues. The Workman and U.S.N. Standard values are identical for the 5-, 10-, and 20-min half-time tissues.

As with the linear extrapolations of M_0 values, we calculated the altitudes at which the constant ratio derived M_0 values attained an absolute value of 26.1 fswa. This information for the longer half-times (i.e., 120 - 240 min) is presented in Table 8.

Based on the well-documented fact that the threshold altitude for decompression sickness in sea-level-equilibrated individuals is 18,000 ft above sea level, the M_0 values derived by using a constant R_0 would appear to

TABLE 6. EXTRAPOLATION OF U.S.N. STANDARD AIR DECOMPRESSION TABLE M_0 VALUES USING A CONSTANT R_0

Altitude	Absolute pressure (fswa)	Tissue half-times 5	10	20	40	80	120
Sea level	33	104	88	72	58	52	51
4,500 ft	28	88.2	74.8	61.0	49.3	44.2	43.4
7,000 ft	25.5	80.3	68.1	55.6	44.9	40.3	39.5
9,500 ft	23	72.5	61.4	50.1	40.5	36.3	35.7
R_0		3.15	2.67	2.18	1.76	1.58	1.55

TABLE 7. EXTRAPOLATION OF WORKMAN'S M_0 VALUES USING A CONSTANT R_0

Altitude	Absolute pressure (fswa)	Tissue half-times 5	10	20	40	80	120	160	200	240
Sea level	33	104	88	72	56	54	52	51	51	50
4,500 ft	28	88.2	74.8	61.0	47.6	45.9	44.2	43.4	43.4	42.6
7,000 ft	25.5	80.3	68.1	55.6	43.4	41.8	40.3	39.5	39.5	38.8
9,500 ft	23	72.5	61.4	50.1	39.1	37.7	36.3	35.7	35.7	35.0
R_0		3.15	2.67	2.18	1.70	1.64	1.58	1.55	1.55	1.52

TABLE 8. ALTITUDES AT WHICH M_0 = 26 FSWA FOR THE 120-, 160-, 200-, AND 240-MIN HALF-TIME TISSUES OBTAINED USING CONSTANT R_0 VALUES

Tissue half-time	120 min	160 min	200 min	240 min
U.S.N. values	17,500 ft	N/A	N/A	N/A
Workman's values	18,000 ft	17,500 ft	17,500 ft	17,000 ft

provide M_0 values which would be safe for calculation of or evaluation of altitude diving tables. Historically, this procedure has been the basis for calculating specialized dive profiles for the USAF Aerospace Rescue and Recovery Service personnel who have had operational requirements for flying immediately after diving. No difficulties are known to have occurred in these operations.

One additional relationship that was evaluated, with respect to selecting the most "valid" set of values for application to hyperbaric exposures at altitude, was the slowest half-time to be considered for such exposures. The U.S.N. Standard Diving Tables set of values uses 120 min as the slowest half-time for calculating sea-level dives, while the Workman values have a 240-min half-time as the slowest compartment. In order to evaluate these half-times, the following conditions (a - c) were established on the basis of well-documented data obtained in altitude bends studies conducted in the past at the USAFSAM:

a. 35,000 ft altitude exposure following ground-level denitrogenation using F_{IO2} = 1.0

b. 35,000 ft = 7.8 fswa

c. Half-time tissues and ratios used to calculate the time required to denitrogenate at sea level for a safe altitude exposure were: 120 min/1.55; and 240 min/1.52.

The denitrogenation times calculated for the specified conditions were 2.2 hr using the 120-min half-time tissue, and 4.6 hr using the 240-min half-time tissue. Therefore, if the known requirement of at least a 4-hr denitrogenation prior to an exposure to 35,000 ft is taken into account, the slowest compartment that should be considered in hyperbaric exposures at altitude is the 240-min half-time tissue of Workman, using an R_0 of 1.52.

By use of the data thus derived, a full set of M_D values were calculated for an altitude of 10,000 ft above sea level (Table 9).

B. Calculation of no-decompression limits for dives followed by immediate ascent to 10,000 ft above sea level

By means of a program developed for the Hewlett Packard HP-65 programmable pocket calculator by Bassett and Christopherson (15), and of the M_D and R_D values just described, exposure times were calculated for the selected depths. In addition, the maximum depth at which an individual could be saturated and still ascend directly to 10,000 ft above sea level was calculated. The calculated exposure limits for depths to 130 fsw are listed in Table 10. Presented in Table 11 are the calculated tissue nitrogen tensions in 9 half-time compartments: (A) upon surfacing from the dive; (B) upon reaching 10,000 ft above sea level; and (C) after 4 hours exposure at 10,000 ft.

TABLE 9. TABLE OF M VALUES

Altitude (feet above sea level):	10,000 ft = 22.7 fswa		PN_2 = 17.96 fswa					
Depth of decompression stop:			10	20	30	40	50	60
Equivalent abs. depth (fswa):			32.7	42.7	52.7	62.7	72.7	82.7
Equiv. abs. depth - Next stop			22.7	32.7	42.7	52.7	62.7	72.7
Half-times	$\Delta M_D/\Delta$ 10 fsw							
5	18	M_D	71.5	89.5	107.5	125.5	143.5	161.5
		R_D	3.15	2.74	2.52	2.38	2.29	2.22
10	16	M_D	60.6	76.6	92.6	108.6	124.6	140.6
		R_D	2.67	2.34	2.17	2.06	1.99	1.93
20	15	M_D	49.5	64.5	79.5	94.5	109.5	124.5
		R_D	2.18	1.97	1.86	1.79	1.75	1.71
40	14	M_D	58.6	52.6	66.6	80.6	94.6	108.6
		R_D	1.70	1.61	1.56	1.53	1.51	1.49
80	13	M_D	35.9	48.9	61.9	74.9	87.9	100.9
		R_D	1.58	1.50	1.45	1.42	1.40	1.39
120	11.5	M_D	35.2	47.2	59.2	71.2	83.2	95.2
		R_D	1.55	1.44	1.39	1.35	1.33	1.31
160	11	M_D	35.2	46.7	58.2	69.7	81.2	92.7
		R_D	1.55	1.43	1.36	1.32	1.30	1.28
200	11	M_D	35.2	46.2	57.2	68.2	79.2	90.2
		R_D	1.55	1.41	1.34	1.29	1.26	1.24
240	11	M_D	34.5	45.5	56.5	67.5	78.5	89.5
		R_D	1.52	1.39	1.32	1.28	1.25	1.23

TABLE 10. CALCULATED EXPOSURE LIMITS

Depth (fsw)	No-decompression limit (min) for direct ascent to 10,000 ft
10.75[a]	1440 +
20	120
30	52
40[a]	34
50	26
60[a]	20
70	16
80[a]	14
90	12
100[a]	10
110	9
120	8
130[a]	7

[a]Profiles selected for manned validation tests.

For the 6 exposure profiles, none of the calculated tissue nitrogen levels are close to the limiting M_D values allowed by the U.S. Navy Standard Air Decompression Tables (12) for surfacing at sea level (Table 11). Upon exposure to 10,000 ft above sea level, all calculated tissue nitrogen levels are equal to or less than the desired limiting M_D values. The saturation exposure at 10.75 fsw brings the 240-min half-time compartment to the M_D limit. All other exposures result in only the 40-min half-time compartment reaching the M_D limit. Finally, upon leaving 10,000 ft above sea level, all half-time compartment levels are less than the M_D values calculated for exposure to 16,000 ft above sea level.

C. Manned Validation Test Design

1. Exposure Profiles

Each of the 6 exposure schedules were to be validated by 20 manned exposures, in which hyperbaric and altitude chambers were utilized to simulate the barometric pressures involved. Two volunteer military divers were used per test. During the hyperbaric exposures, except for the saturation exposure, the test subjects performed moderate step-test exercise during approximately 50% of the exposure time at depth. No exercise was performed during the saturation exposure. Ascent to sea level was made at rest, at a rate of approximately 1 fsw/sec; and transfer to the altitude chamber required approximately 1 min. Ascent to 10,000-ft altitude was performed, with the subjects breathing ambient chamber air, at a rate such that 10,000 ft was attained 5 min after the subjects surfaced from the dive. The test subjects remained at 10,000 ft for 4 hr--unless the exposure was terminated--during which time they engaged in intermittent (5 min each 30 min) stepping-in-place activity. At the end of this period the subjects were taken to 16,000 ft in 1.5 min, and remained at that altitude at rest for 1 hr using diluter-demand oxygen equipment. The exposure profile was terminated with a 4,000 fpm descent to ground level. Each subject was exposed to 2 different schedules with 7 days between exposures.

2. Monitoring for Venous Gas Emboli (vge)

The test subjects were monitored for vge--once, prior to the hyperbaric exposure; and intermittently, during the altitude exposure using the precordial Doppler ultrasonic bubble detector, as described by Spencer et al. (16). Each subject was monitored: at 10,000 ft, for five 2-min periods during the first hour of exposure, two 2-min periods during the second and third hours, and three 2-min periods in the final hour; and, at 16,000 ft, for five 2-min periods during the 1-hr exposure.

During each 2-min period of monitoring, the subject sat at rest for the first minute and was asked to passively flex each extremity--one at a time--three times at the start of the second minute of monitoring. The Doppler signal was monitored by the investigator (who accompanied the test subjects) using earphones, and was also recorded on magnetic tape cassettes.

TABLE 11. CALCULATED TISSUE NITROGEN TENSIONS FOR 6 EXPOSURE PROFILES

Half-times	Exposure profiles 130/7	100/10	80/14	60/20	40/34	10.75/1440	M_D values
	A. Tissue PN_2 upon reaching sea level						
5	86.7	81.3	76.5	67.9	56.1	34.5	104
10	67.3	65.6	64.7	60.9	54.1	34.5	88
20	50.3	50.1	50.7	49.8	47.9	34.6	72
40	39.3	39.4	40.1	40.1	40.1	34.6	56
80	33.0	33.1	33.5	33.7	34.2	34.6	52
120	30.7	30.8	31.1	31.3	31.7	34.6	51
160	29.6	29.7	29.9	30.1	30.4	34.6	51
200	28.9	28.9	29.1	29.3	29.5	34.6	51
240	28.4	28.4	28.6	28.7	29.0	34.5	50
	B. Tissue PN_2 upon reaching 10,000 ft						
5	54.3	51.6	49.2	44.9	39.0	28.2	71.5
10	54.0	52.8	52.2	49.5	44.7	30.9	60.6
20	45.8	45.6	46.1	45.4	43.8	32.6	49.5
40	37.9	38.0	38.6	38.6	38.6	33.6	38.6
80	32.5	32.6	33.0	33.2	33.7	34.1	35.9
120	30.5	30.6	30.8	31.0	31.4	34.2	35.2
160	29.4	29.5	29.7	29.9	30.2	34.3	35.2
200	28.8	28.8	29.0	29.2	29.4	34.4	35.2
240	28.3	28.3	28.5	28.6	28.9	34.4	34.5

(Cont'd. on facing page)

TABLE 11 (Cont'd. from facing page)

Half-times	Exposure profiles 130/7	100/10	80/14	60/20	40/34	10.75/1440	M_D values
	C. Tissue PN_2 upon leaving 10,000 ft						
5	17.8	17.8	17.8	17.8	17.8	17.8	56.4
10	17.8	17.8	17.8	17.8	17.8	17.8	47.8
20	17.8	17.8	17.8	17.8	17.8	17.8	39.0
40	18.1	18.1	18.1	18.1	18.1	18.0	30.4
80	19.6	19.7	19.7	19.7	19.8	19.8	28.3
120	21.0	21.0	21.1	21.1	21.2	21.9	27.8
160	21.9	21.9	22.0	22.1	22.2	23.6	27.8
200	22.6	22.6	22.7	22.8	22.9	25.0	27.8
240	23.1	23.1	23.2	23.2	23.4	26.1	27.2

Termination of the altitude exposure resulted from a vge score, as described by Spencer (17), of 3 during the resting portion of the monitoring period, or a score of 4 during the period of and following flexing of the extremities. In the event of subjective or objective signs or symptoms of decompression sickness, the exposure was terminated regardless of the Doppler vge score.

IV. RESULTS: FAD-I

A. Overall Results

A total of 63 volunteer military divers participated in one or more flying-after-diving exposures. When an exposure was terminated for one subject, it was terminated for the second subject regardless of his vge score. The exposure of the second subject was not then included in the totals (Table 12). Also, if equipment problems caused early termination of an exposure, it was not included in the totals. Therefore, a corrected total of 59 volunteer test subjects participated in 110 flying-after-diving exposures. The results of these exposures, according to the dive profile (depth and total bottom time), are presented in Table 12.

On the basis of the overall results, 4 subgroups were established. The following groups were assigned to those individuals who experienced: symptoms

TABLE 12. OVERALL RESULTS BY DIVE PROFILE

Dive profile	Number of manned exposures	Bends-flight aborted	vge-flight aborted	vge-flight completed	No vge produced
130/7	20	0	0	0	20
100/10	18	1	0	6	11
80/14	16	1	3	2	10
60/20	18	1	1	3	13
40/34	18	1	1	2	14
10.75/1440	20	1	2	1	16
Total:	110	5	7	14	84
Percent of total:		(4.55 %)	(6.36 %)	(12.73 %)	(76.36 %)

of pain-only bends on one or more exposures--Group 1; high vge scores, which resulted in aborting the altitude exposure before completion--Group 2; only slight to moderate vge, which did not result in aborting the altitude exposure--Group 3; and no vge on all of their exposures--Group 4. The exposure experience by each of these groups is given in Table 13.

Slight differences were noted between the actual and the calculated exposures in terms of descent, ascent, and exposure times of the hyperbaric exposures (dive). Presented in Table 14 are: (A) the calculated mean values for descent, exposure, and ascent times for the dives; (B) the calculated mean tissue PN_2 upon reaching 10,000 ft; and (C) the results in terms of vge, aborts, and bends experienced.

B. Individual Factors

Comparisons between groups with respect to age and percent body fat are presented in Table 15. These two factors can possibly play a role in individual susceptibility to decompression sickness.

C. Details of Bends and vge Exposure Groups

1. The Bends Group (4 subjects: 8 exposures; 5 bends; 3, no vge)

One subject experienced mild bends pain after 7-min exposure at 16,000 ft. One subject experienced mild bends pain on two separate exposures, both at 16,000 ft after 45- and 50-min exposure time at that altitude. One subject experienced vague discomfort, after 240 min at 10,000 ft, which

TABLE 13. GROUP EXPOSURE EXPERIENCE

Group	Number of subjects	Total exposures	Total bends exposures	vge abort	vge completed	No vge
1	4	8	5			3
2	6	10		7	2	1
3	10	20			12	8
4	39	72				72
Total:	59	110	5	7	14	84
Percent of total:			(4.55 %)	(6.36 %)	(12.73 %)	(76.36 %)

developed into mild bends pain by 22 min at 16,000 ft. One subject had onset of mild to moderate pain after 90 min at 10,000 ft. All subjects presented vge prior to onset of bends; and all symptoms were promptly relieved by descent, with all pain being gone before ground level was reached. No vge was detected after 15 - 45 min at ground level. No subjects required hyperbaric therapy. Except for the subject who experienced bends pain on both exposures, all 3 other subjects completed one other exposure without detection of vge.

2. The vge Abort Group (6 subjects: 10 exposures; 7 vge aborts; 2 vge completed; 1, no vge)

At the end of 240 min at 10,000 ft, 5 subjects had a sufficiently high vge score to warrant aborting the flight without ascent to 16,000 ft. One of these 5 subjects also, on a subsequent exposure, had a sufficiently high vge score at the end of 120 min at 10,000 ft to abort his second flight. Of the 5 subjects, 2 did not have a second exposure. One additional subject had two exposures which produced vge at 16,000 ft--one flight being completed and the other being aborted, due to the vge score, after 25 min at 16,000 ft.

3. The vge Flight-Completed Group (10 subjects: 20 exposures; 12 with vge; 8, no vge)

Two subjects displayed low vge scores on both of their exposures, after 15 - 50 min at 16,000 ft only. Of the 3 subjects who had transient low vge scores at 10,000 ft, 2 also displayed low vge scores later at 16,000 ft. None of these subjects produced vge on their additional exposures. The remaining 5 subjects had very low vge scores only at 16,000 ft on only one of their two exposures.

TABLE 14. THE FAD-I ACTUAL EXPOSURE PARAMETERS, CALCULATED MEAN TISSUE PN_2 UPON REACHING 10,000 FT, AND RESULTS

A. The FAD-I actual exposure parameters

Mean values	Schedules					
	130/7	100/10	80/14	60/20	40/34	10.75/1440
Mean descent time (min)	2.53	1.68	1.64	1.10	1.10	N/A
Mean exposure time (min)	4.47	8.33	12.36	18.90	32.90	1440
Mean ascent time (min)	2.68	2.08	1.76	1.33	0.96	0.88

B. *Calculated mean tissue PN_2d (fswa) upon reaching 10,000 ft*

Half-times	M-value	Mean tissue PN_2 (fswa)					
5	71.5	51.2	50.2	48.2	44.4	38.7	28.0
10	60.6	50.7	51.3	51.1	49.0	44.5	30.8
20	49.5	43.4	44.5	45.4	45.0	43.5	32.5
40	38.6	36.3	37.2	38.1	38.3	38.5	33.5
80	35.9	31.7	32.2	32.8	33.1	33.6	34.1
120	35.2	29.9	30.3	30.7	30.9	31.4	34.2
160	35.2	29.0	29.2	29.5	29.7	30.2	34.3
200	35.2	28.5	28.7	29.0	29.1	29.4	34.4
240	34.5	28.0	28.2	28.5	28.6	28.9	34.3

C. RESULTS

Groups	Number of:					
Manned exposures	20	18	16	18	18	20
vge at 10,000 ft	0	1	3	3	3	3
vge aborts at 10,000 ft	0	0	2	1	1	2
Bends at 10,000 ft	0	0	1	0	0	0
vge at 16,000 ft	0	7	3	3	3	2
vge aborts at 16,000 ft	0	0	1	0	0	0
Bends at 16,000 ft	0	1	0	1	1	1
Total aborts	0	1	4	2	2	3
Skin "bends"	18	14	7	6	0	0

V. DISCUSSION OF FAD-I RESULTS

A. Incidence of Bends and/or vge at 10,000 Ft

1. Of the exposures, 11.8% (n = 13) produced detectable vge at 10,000 ft. Of the altitude exposures, 6.4% (n = 7) were terminated at 10,000 ft due to bends (1 case) or vge scores of 4 (6 cases). (At least this incidence, if not a greater one, would reasonably have been expected if the exposures had involved actual dives and aircraft flight.) These cases were encountered on all exposure schedules, except the 130/7 and 100/10. By design, the exposure to 10,000 ft after these 6 dive schedules was no more stressful, from a decompression standpoint, than dives made within established U.S. Navy "no decompression" time limits at sea level. An overall incidence of decompression sickness in U.S. Navy experience with the Standard Air Decompression Tables has been cited as 0.03% to 0.41% (refer to par. III, A. 6, of our report). A more recent report (18) cites a more realistic operational incidence, in U.S. Navy divers, of 1.25% to 1.5%. This higher incidence results from omitting dives which are far short of the limits of the U.S. Navy Tables; i.e., those which could not possibly result in decompression sickness. However, even when dives are reported as having been made on a specific schedule (i.e., 100/25, 60/60, etc.), only a fraction would be made to the actual depth and time limits, because each schedule represents a 10-ft range in depth and a 5-or-more-minutes range in time. In other words, dives made to 91, 92, 93, 94, 95, 96, 97, 98, 99, or 100 ft for 21, 22, 23, 24, or 25 min would be recorded as 100/25 dives. When dives are made in the laboratory (as in this study), depth and time are controlled and the results are interpreted to be the "true" incidence.

2. Of the six exposures which produced detectable vge at 10,000 ft but which were not aborted at that altitude, 2 cases had the onset of a vge score of 3 to 4 and then bends at 16,000 ft (1 case each on the 10.75/1440 and 60/20 schedules). In 1 case, the vge score of 1 at 10,000 ft increased to 2 to 3 at 16,000 ft. The remaining 3 cases had only transient vge scores of 1 or 2 at both altitudes. These latter cases were considered insignificant, and may have represented a false positive interpretation of the Doppler signals.

3. Skin "bends" (itches) were positively correlated with exposure depth, with: 90% occurrences in subjects exposed to the 130/7 schedule; 78%, to the 100/10; 44%, to the 80/14; 33%, to the 60/20; and none to the 40/34 and the 10.75/1440. This phenomenon had no correlation with detectable vge or bends. The actual cause of this phenomenon has not been determined. The itches occurred on ascent to, or immediately upon arrival at, 10,000 ft. In the mildest cases, the itches spontaneously relieved within 5 - 10 min or, in the severest cases, within 60 min.

B. Incidence of Bends and/or vge at 16,000 Ft

1. In addition to the two exposures which produced detectable vge at 10,000 ft and subsequent bends at 16,000 ft, 3.9% (n = 3) of the 103 exposures to 16,000 ft were terminated due to bends (2 cases), or vge scores of 4 (1 case), which were not preceded by vge at 10,000 ft. These cases occurred on the 100/10, 80/14, and 40/34 schedules. Examination of Table 11, Part C,

TABLE 15. COMPARISON OF AGE AND PERCENT BODY FAT IN GROUPS: FAD-I

Group number	Age ($\overline{X} \pm$ S.D.)	Percent body fat ($\overline{X} \pm$ S.D.)	Subjects in group	Significance in difference compared to Group 4: Age	Body fat
1	37.25 ± 5.62 (30 - 43)	19.16 ± 7.03 (11.82 - 28.54)	4	P<0.001	P<0.01
2	25.83 ± 5.04 (20 - 33)	15.07 ± 2.56 (12.39 - 18.41)	6	N.S.	N.S.
3	31.30 ± 8.77 (21 - 48)	19.87 ± 5.46 (11.85 - 29.37)	10	P<0.01	P<0.01
4	24.62 ± 4.33 (18 - 36)	15.31 ± 4.51 (7.26 - 29.42)	39	———	———
1 + 2	30.40 ± 7.71 (20 - 43)	16.70 ± 4.96 (11.82 - 28.54)	10	P<0.01	N.S.
1 + 2 + 3	30.85 ± 8.05	18.29 ± 5.33	20	P<0.001	P<0.05
All groups	26.59 ± 6.36 (18 - 48)	16.15 ± 5.13 (7.26 - 29.42)	59		

reveals that the calculated tissue PN_2 in all half-time compartments was much lower at the end of 4 hr at 10,000 ft than the calculated allowable maximum tissue PN_2 values (M_D values) for ascent to 16,000 ft. That vge were formed during the pressure reduction from 10,000 to 16,000 ft is therefore unlikely; but undetected vge present at 10,000 ft may have expanded to detectable size with the pressure reduction.

2. An additional 9.4% (n = 10) of the exposures at 16,000 ft produced detectable vge; but the vge scores did not call for termination of the flight. Three of these cases had vge scores of 3; the remaining 7 had only transient scores of 1, and were also considered to be insignificant.

3. No cases of skin "bends" were produced by the ascent from 10,000 to 16,000 ft.

C. Recommendations and FAD-II Testing

1. Since 10.9% (n = 12) of the 110 exposures were terminated because of bends (n = 5) or vge scores of 4 (n = 7), the tested exposure schedules could not be recommended for use in military operational diving. Reducing the exposure time at depth was not considered a viable option, since the calculated exposure schedules were minimal in terms of useful dive time. After the matter had been discussed with Staff Surgeon representatives of the USAF Aerospace Rescue and Recovery Service (ARRS), the decision was made to modify the exposure profiles by reducing the altitudes from 10,000 to 8,500 ft, and from 16,000 to 14,250 ft. All other exposure parameters were to remain the same, and additional manned validation testing was resumed.

2. Due to budget and time constraints, the FAD-II validation tests were conducted on 3 of the original 6 exposure schedules; specifically, the 100/10, 80/14, and 60/20 schedules. Since no vge or bends occurred on the 130/7 schedule in FAD-I tests, this schedule was considered to be validated at the lower altitude without testing. The saturation schedule of FAD-I (i.e., 10.75/1440) was not tested in FAD-II, because the FAD-I schedule was considered to be of academic, rather than operational, significance. The 40/34 schedule was not tested, since it matched the 60/20 schedule (refer to Table 14) so closely in terms of mean calculated tissue PN_2's and vge and/or bends produced.

3. Test subjects in FAD-II were not military divers but were recruited from the USAFSAM volunteer test subject pool. They received a thorough briefing on the hyperbaric environment and protocol, and participated in a training hyperbaric chamber dive to 100 fsw before participating in the FAD-II tests. Many of the subjects who participated had a previous history of detected vge and/or bends on other protocols involving only altitude exposure.

4. The manned validation test design for FAD-II, except for the altitudes, was identical to that for FAD-I (as described in section IV: Parts C-1 and C-2 of this report). By keeping the dive exposures the same, the M_D values (maximum allowable calculated tissue PN_2 values) for exposure to altitude remain the same (Table 9); however, the allowable R_D values (PN_2/P_B ratio; i.e., supersaturation ratios) are reduced (Table 16).

TABLE 16. COMPARISON OF SURFACING M_D AND R_D VALUES IN FAD-I AND FAD-II EXPOSURES

Half-time tissue	M_D (fswa) values 10,000 ft	8,500 ft	R_D values 10,000 ft	8,500 ft
5	71.5	71.5	3.15	2.98
10	60.6	60.6	2.67	2.53
20	49.5	49.5	2.18	2.06
40	38.6	38.6	1.70	1.61
80	35.9	35.9	1.58	1.50
120	35.2	35.2	1.55	1.47
160	35.2	35.2	1.55	1.47
200	35.2	35.2	1.55	1.47
240	34.5	34.5	1.52	1.44

10,000 ft = 22.7 fswa
8,500 ft = 24.0 fswa

VI. RESULTS: FAD-II

A. Overall Results

A total of 28 volunteer subjects participated in one or more flying-after-diving exposures, thus resulting in 57 manned test exposures. The results of these exposures, according to the dive profile (depth and/total bottom time), are presented in Table 17.

Subgroups 1 - 4 were established on the basis of the overall results. Group 1 consisted of the one individual who might have experienced bends pain on one of his two exposures. Group 2 consisted of the two individuals who experienced high vge scores which resulted in aborting the altitude exposure before completion. Group 3 included those individuals who experienced slight to moderate vge, which did not result in aborting the altitude exposure. Group 4 were those subjects who were vge-free on all of their exposures. The exposure experience by each of these groups is presented in Table 18.

The actual exposures differed from the calculated exposures in terms of slight differences in descent, ascent, and exposure times of the hyperbaric

TABLE 17. THE FAD-II OVERALL RESULTS BY DIVE PROFILE

Dive profile	Number of manned exposures	Bends-flight aborted	vge-flight aborted	vge-flight completed	No vge produced
100/10	20	0	1	5	14
80/14	19	0	0	7	12
60/20	18	1[a]	1	4	12
Total:	57	1[a]	2	16	38
Percent of total:		(1.75 %)	(3.51 %)	(28.07 %)	(66.67 %)

[a]Atypical Type I bends possible.

TABLE 18. EXPOSURE EXPERIENCE OF GROUPS

Group	Number of subjects	Number of exposures	Incidence of bends	vge abort	vge completed	No vge
1	1	2	1		1	
2	2	3		2	1	
3	10	22			14	8
4	15	30				30
Total:	28	57	1	2	16	38
Percent of total:			(1.75 %)	(3.51 %)	(28.07 %)	(66.67 %)

exposure. Given in Table 19 are: (A) the calculated mean values for descent, exposure, and ascent times for the dives; (B) the calculated mean tissue PN_2 and R_s values upon reaching 8,500 ft; and (C) the results in terms of vge, aborts, and bends experienced.

B. Individual Factors

Comparisons of groups with respect to age and percent body fat are presented in Table 20. These two factors have been noted as possibly playing a role in individual susceptibility to decompression sickness.

C. Details of Bends and vge Exposure Groups

1. The Bends Group (1 subject: 2 exposures, 1 bends, 1 vge completed)

The subject who experienced what may have been mild bends pain, after 20 min at 14,250 ft, had been on the 60/20 dive schedule. The pain was experienced in the left upper quadrant of the chest, along the ribs. He had the onset of vge scores of 1 - 2 as soon as 14,250 ft was reached. The vge score increased to 3 at 20 min, just before he noted discomfort and/or pain. The vge and the pain resolved on 100% oxygen with descent to ground level. The subject admitted having extensive physical activity 3 days prior to exposure, and had stiff, sore muscles which he tried to relieve with stretching exercises while at altitude. Also of note, the vge scores were not related to movement of the extremities. On his second exposure, to the 80/14 dive schedule, this subject had possible occasional vge scores of 1 at arrival, and at 30 and 90 min at 8,500 ft, but no vge detected at 14,250 ft.

2. The vge Abort Group (2 subjects: 3 exposures; 2 vge aborts; 1 vge completed)

Two subjects had sufficiently high vge scores to terminate the exposure while at 14,250 ft. One subject, exposed to the 60/20 dive schedule, had possible vge scores of 1 during exposure at 8,500 ft, of 3 after 10 min, and of 4 after 20 min at 14,250 ft, at which time the flight was aborted. On a previous exposure to the 100/10 dive schedule, this same subject had no vge at 8,500 ft, but had vge which progressed from a score of 1 to a score of 4 during the 1 hr at 14,250 ft. The other subject had only one exposure to the 100/10 dive schedule, and experienced vge with a score of 1 - 2 from 90-230 min at 8,500 ft. The score increased to 4 at 10 min at 14,250, and the flight terminated after 15 min at this altitude.

3. The vge Flight-Completed Group (10 subjects: 22 exposures: 14 with vge; 8, no vge)

Three subjects had low vge scores on both of their exposures. Two of these subjects had possible vge scores of 1 - 2, transiently, at 8,500 ft--increasing to probable scores of 3 during the hour at 14,250 ft. The third subject had only possible vge scores of 1, only at 14,250 ft. Five subjects had low vge scores on only one of two exposures. Two of these subjects had only questionable vge scores of 1 at 14,250 ft in both cases, and at 8,500 ft

TABLE 19. THE FAD-II ACTUAL EXPOSURE PARAMETERS, CALCULATED MEAN TISSUE PN_2 AND R_S VALUES UPON REACHING 8,500 FT, AND RESULTS

A. The FAD-II actual exposure parameters

Mean values	Schedules 100/10	80/14	60/20
Mean descent time (min)	1.83	1.36	1.09
Mean exposure time (min)	8.17	12.64	18.91
Mean ascent time (min)	2.00	1.55	1.19

B. Calculated mean tissue PN_2 and R_S values (fswa) upon reaching 8,500 ft

Half-time	M-value	PN_2	R_S	PN_2	R_S	PN_2	R_S
5	71.5	50.5	2.11	48.9	2.04	44.9	1.87
10	60.6	51.4	2.14	51.5	2.15	49.2	2.05
20	49.5	44.5	1.85	45.6	1.90	45.1	1.88
40	38.6	37.3	1.55	38.2	1.59	38.5	1.60
80	35.9	32.3	1.35	32.8	1.37	33.1	1.38
120	35.2	30.3	1.26	30.8	1.28	31.1	1.29
160	35.2	29.3	1.22	29.7	1.24	29.8	1.24
200	35.2	28.8	1.20	29.1	1.21	29.2	1.22
240	34.5	28.3	1.18	28.5	1.19	28.7	1.20

C. RESULTS

Groups	Number of:		
Manned exposures	20	19	18
vge at 8,500 ft	4	5	2
vge aborts at 8,500 ft	0	0	0
Bends at 8,500 ft	0	0	0
vge at 14,250 ft	6	6	6
vge aborts at 14,250 ft	1	0	1
Bends at 14,250 ft	0	0	1
Total aborts	1	0	2
Skin "bends"	11	1	0

in one case. The other 3 subjects had definite vge scores of from 1 - 4 during the 1 hr at 14,250 ft, with 2 of the 3 having had possible transient vge scores of 1 - 2 at 8,500 ft. One subject had vge scores of 1 - 3 while at 14,250 ft on two of three exposures, with possible scores of 1 while at 8,500 ft on one of these two exposures. The remaining subject had vge scores of 1 - 3 while at 14,250 ft on only one of three exposures.

VII. DISCUSSION OF FAD-II RESULTS

A. Incidence of Bends and/or vge at 8,500 Ft

1. Of the exposures, 19.3% (n = 11) produced detectable vge at 8,500 ft. However, none of the altitude exposures were terminated at 8,500 ft because of bends or vge scores of 4. Furthermore, only 2 of the 11 exposures which produced vge at 8,500 ft had to be terminated at 14,250 ft for vge scores of 4. In two additional cases, the vge score did not increase after ascent to 14,250 ft. In the remaining 7 cases, the vge scores increased after ascent to 14,250 ft, but not to the extent that termination of the flight was deemed necessary. Because no exposures were terminated at 8,500 ft, the schedules tested were judged to be validated for use by military divers with the operational requirement to fly to 8,500 ft at either absolute pressure altitude or at cabin altitude immediately after diving with open-circuit scuba.

2. As in the FAD-I results, skin "bends" (itches) were positively correlated with exposure depth, with: 55% occurrence on the 100/10 schedule; 5% occurrence on the 80/14; and none on the 60/20. Also paralleling the FAD-I results, skin itches had no correlation with detectable vge or bends. However, comparison between FAD-I and FAD-II results indicates that lowering the initial altitude from 10,000 to 8,500 ft reduces the overall incidence of this phenomenon from 41% to 21%. The two parameters changed were the absolute pressure decrease (from maximum depth to flight altitude) and the calculated surfacing ratio (R_S values) for the half-time tissues, both of which can be seen as measures of decompression stress. Therefore, the incidence of skin "bends" is directly related to, and perhaps a sensitive indicator of, decompression stress--even though the exact mechanism of the phenomenon is not understood. Also noteworthy is the fact that the itches experienced in the FAD-II exposures were only of the mildest form, relieved spontaneously within 5 - 10 min.

B. Incidence of Bends and/or vge at 14,250 Ft

1. Of the exposures, 5.26% (n = 3) were terminated sooner than 1 hr of exposure to 14,250 ft. Two of these exposures were aborted, with vge scores of 4 occurring within the first 15 - 20 min at that altitude; and, in both cases, the subjects had also had possible vge scores of 1 during exposure at 8,500 ft. Two subjects with scores of 1 at 8,500 ft also progressed to scores of 4 at 14,250 ft, but only at or near the end of the 1 hr of exposure time. Five exposures which had scores of 1 at 8,500 ft progressed to scores of 3 during the 1 hr at 14,250 ft. Without detectable vge at 8,500 ft, 2 cases developed scores progressing from 1 - 4 during the 1 hr at 14,250 ft; and two more cases, from 1 - 3 at 14,250 ft. Two exposures

TABLE 20. COMPARISON OF AGE AND PERCENT BODY FAT IN GROUPS: FAD-II

Group number	Age ($\overline{X} \pm$ S.D.)	Percent body fat ($\overline{X} \pm$ S.D.)	Subjects in group	Significance in difference compared to Group 4: Age	Body fat
1	28	12.08	1	N/A	N/A
2	36.5 ± 4.95 (33 - 40)	22.86 ± 2.36 (21.19 - 24.53)	2	$P<0.2$	$P<0.8$
3	34.3 ± 8.30 (22 - 45)	19.00 ± 5.09 (9.38 - 26.46)	10	$P<0.05$	$P<0.8$
4	29.13 ± 7.09 (20 - 42)	17.79 ± 8.79 (8.14 - 36.21)	15	———	———
1 + 2	33.67 ± 6.03 (28 - 40)	19.27 ± 6.44 (12.08 - 24.53)	3	$P<0.4$	$P<0.8$
1 + 2 + 3	34.15 ± 7.60 (22 - 45)	19.06 ± 5.13 (9.38 - 26.46)	13	$P<0.1$	$P<0.8$
All groups	31.46 ± 7.63 (20 - 45)	18.40 ± 7.16 (8.14 - 36.21)	28		

resulted in possible vge scores of 1 only at 14,250 ft, with an additional exposure showing possible vge scores of 1 at both 8,500 and 14,250 ft. These exposures were considered insignificant and likely to be false positive Doppler interpretations.

2. The one case terminated because of bends, after 20 min at 14,250 ft, remains the only near serious failure in this test series. However (as discussed in section VI, Par. C.1), if this subject did in fact have bends, the influence of recent muscle injury must be taken into account. This influence is likely to explain his case; for a second exposure, 5 - 6 weeks later, resulted merely in a transient possible vge score of 1 only at 8,500 ft (i.e., false positive). With this one case of atypical bends, the incidence in the FAD-II tests was 1.75% as compared to 4.55% in the FAD-I tests.

C. Consideration of Individual Factors

1. In the FAD-I series of tests, a total of 59 subjects were used, 5 of whom had previously experienced decompression sickness on one or more occasions in their diving careers. One subject with 3 prior occurrences had bends on both of his FAD exposures. Two of the others had minor vge scores on one of two FAD exposures. The remaining 2 individuals had no detectable vge on any of their FAD exposures. Of the 28 subjects used in the FAD-II series, 10 had previously experienced bends on one or more occasions on altitude decompression protocols, and an additional 4 had previously experienced high score (3 or 4) vge on similar protocols. Of the three exposures which were terminated in FAD-II, however, only one occurred in a subject who had previously experienced bends. The other 2 cases, including the subject with atypical bends in FAD-II, had no prior experience with bends. Nine subjects with prior bends or vge had no vge detected in their FAD-II exposures. The remaining 4 subjects with prior histories did experience some vge production on their FAD-II exposures. While the numbers are small, they reveal that 60% (3 of 5) of the subjects who could be classified as susceptible experienced either bends or vge production in FAD-I exposures--but only 35.7% (5 of 14) of the susceptible subjects had such experiences in FAD-II exposures. This finding is taken as further evidence that the FAD-II exposures represent a reduced decompression stress as compared with those in FAD-I.

2. Comparison of the mean ages and percent body fat between the two groups (FAD-II vs. FAD-I) reveals that the FAD-II subjects were significantly older (31.46 ± 7.63 yr vs. 26.59 ± 6.36 yr, $p<0.01$) than the FAD-I subjects, and tended to have a higher percent body fat (18.40 ± 7.16% vs. 16.18 ± 5.13%, $p<0.1$). Since the general belief is that both increased age and body fat augment susceptibility to bends, the lower incidence of bends and serious vge in the older, fatter FAD-II subjects can be added evidence of the reduced decompression stress in the FAD-II exposures.

D. Extrapolation to Other Altitudes

Because of the 100% success of the exposures to 8,500 ft after the selected dive schedules, one would expect that the limiting PN_2/PB ratios (R_S values) could be successfully used to calculate maximum tissue PN_2's M_S values) to be used for flight to other altitudes after sea-level diving or for diving at high elevations. Such schedules are contained in Appendix A.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

1. Direct extrapolation of the Surfacing Ratio limits of the U.S. Navy Standard Air Decompression Tables, to allow for safe flying-after-diving schedules, does not prevent decompression problems.

2. Revised Surfacing Ratio limits (i.e., reduced R_S values) have been shown to allow successful calculation of safe flying-after-diving schedules.

B. Recommendations

1. The schedules in Appendix A should be adopted for use by military divers of all services and, specifically, by the Aerospace Rescue and Recovery Service, for operations which require flying after diving.

2. The schedules in Appendix A should be adopted for use by military divers of all services and, specifically, by the Aerospace Rescue and Recovery Service, for operations which require diving at elevations above sea level.

3. A system should be developed, by each agency which utilizes these recommended procedures, to record accurately the utilization and any difficulties encountered, and to send these records to a central repository to add to the data base for these procedures.

4. U.S. Air Force Regulation 50-27, and other regulations which presently restrict flying after diving, must be revised to exclude U.S. Air Force divers who use the recommended procedures.

5. A new set of decompression tables should be generated, from the data obtained in these studies, and be used by the USAF Compression Chamber facilities at Peterson AFB, Colorado, and Ellsworth AFB, South Dakota, and by others, if applicable.

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A P P E N D I X A:

NO-DECOMPRESSION LIMITS FOR FLYING AFTER DIVING, AND DIVING AT ALTITUDES ABOVE SEA LEVEL

APPENDIX A:
NO-DECOMPRESSION LIMITS FOR FLYING AFTER DIVING, AND DIVING AT ALTITUDES ABOVE SEA LEVEL

TABLE A-1. NO-DECOMPRESSION LIMITS FOR SEA-LEVEL DIVES FOLLOWED BY IMMEDIATE (5 MIN) ASCENT TO ALTITUDES UP TO 10,000 FT, AND FOR DIVES MADE AT ALTITUDES WITHIN 12 HR OF ARRIVAL

Linear depth (ft)[a]	No-decompression limits (min)				
	Sea level	2,500 ft	5,000 ft	8,500 ft	10,000 ft
130	10	10	8	7	5
120	12	10	9	8	6
110	15	13	11	9	7
100	20	19	15	10	8
90	25	22	17	12	9
80	30	25	20	14	11
70	40	30	23	16	12
60	50	37	28	20	15
50	70	48	36	26	18
40	120	71	50	34	23
30	220	166	85	52	34
20	None	None	374	120	63

[a]Depth is linearly measured distance beneath the surface, not a pressure equivalent as measured by a depth gauge. (For pressure equivalent depths, refer to Table A-3.)

TABLE A-2. NO-DECOMPRESSION LIMITS FOR DIVES CONDUCTED AFTER AN INTERVAL OF 12 HR AT INDICATED ALTITUDES

Linear depth (ft)[a]	No-decompression limits (min) for indicated altitude 2,500 ft	5,000 ft	8,500 ft	10,000 ft
130	8	7	5	4
120	10	8	6	5
110	12	10	7	6
100	16	13	9	8
90	21	17	11	10
80	27	22	16	13
70	34	29	22	19
60	43	37	29	27
50	57	49	40	37
40	88	72	56	51
30	270	176	102	89
20	None	None	None	667

[a]Depth is linearly measured distance beneath the surface, not a pressure equivalent as measured by a depth gauge. (For pressure equivalent depths, refer to Table A-3.)

TABLE A-3. PRESSURE EQUIVALENT DEPTHS AT INDICATED ALTITUDE

Linear depth (ft)	Pressure equivalent depth (ft) at indicated altitude 2,500 ft	5,000 ft	8,500 ft	10,000 ft
130	127.1	124.5	121	119.7
120	117.1	114.5	111	109.7
110	107.1	104.5	101	99.7
100	97.1	94.5	91	89.7
90	87.1	84.5	81	79.7
80	77.1	74.5	71	69.7
70	67.1	64.5	61	59.7
60	57.1	54.5	51	49.7
50	47.1	44.5	41	39.7
40	37.1	34.5	31	29.7
30	27.1	24.5	21	19.7
20	17.1	14.5	11	9.7